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Integrated BIM-Based LCA for the Entire Building Process Using an Existing Structure for Cost Estimation in the Swiss Context

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Abstract: The building sector has a significant potential to reduce the material resource demand needed for construction and therefore, greenhouse gas (GHG) emissions. Digitalization can help to make use of this potential and improve sustainability throughout the entire building's life cycle. One way to address this potential is through the integration of Life Cycle Assessment (LCA) into the building process by employing Building Information Modeling (BIM). BIM can reduce the effort needed to carry out an LCA, and therefore, facilitate the integration into the building process. A review of current industry practice and scientific literature shows that companies are lacking the incentive to apply LCA. If applied, there are two main approaches. Either the LCA is performed in a simplified way at the beginning of the building process using imprecise techniques, or it is done at the very end when all the needed information is available, but it is too late for decision-making. One reason for this is the lack of methods, workflows and tools to implement BIM-LCA integration over the whole building development. Therefore, the main objective of this study is to develop an integrated BIM-LCA method for the entire building process by relating it to an established workflow. To avoid an additional effort for practitioners, an existing structure for cost estimation in the Swiss context is used. The established method is implemented in a tool and used in a case study in Switzerland to test the approach. The results of this study show that LCA can be performed continuously in each building phase over the entire building process using existing Building Information Modeling (BIM) techniques for cost estimation. The main benefit of this approach is that it simplifies the application of LCA in the building process and therefore gives incentives for companies to apply it. Moreover, the re-work caused by the need for re-entering data and the usage of many different software tools that characterize most of the current LCA practices is minimized. Furthermore, decision-making, both at the element and building levels, is supported.

Keywords: Building Information Modeling (BIM); building process; cost estimation structure embodied environmental impacts; greenhouse gas emissions (GHG); LCA benchmarks; LCA databases; LCA values; Level of Development (LOD); Life Cycle Assessment (LCA)

1. Introduction

The Architecture, Engineering, Construction, and Operations (AECO) industry has a high impact on the environment and is responsible for more than one-third of global greenhouse gas (GHG) emissions. Due to the implementation of energy efficiency regulations in most industrialized building practices in the last years, the operational energy demand and associated GHG emissions of new buildings have been reduced [1]. In consequence, the share of the embodied energy emissions due to the manufacturing, replacement, and disposal of building materials gained importance [2]. The significance of accounting for these embodied environmental impacts is highlighted by the recent report of the World Green Building Council [3]. However, the AECO industry is still lacking to address the need for reducing these impacts adequately.

Life Cycle Assessment (LCA) is a methodology to assess environmental issues holistically throughout the building process. It covers the entire life cycle of buildings from raw materials extraction and processing through the manufacturing of building components, the building's use, and end-of-life. According to Russell-Smith et al. [4], LCA can predict the environmental impact of buildings during their life cycle and support sustainable decisions. LCA is widely used for environmental evaluation in industrial manufacturing practices involving standardized processes [5]. When applied in the AECO industry, LCA becomes more challenging since more complex processes are involved [6]. Within the last years, there has been increased interest in using Building Information Modeling (BIM) as a basis for establishing the inventory of materials needed for the LCA [7–9].

BIM is a 3D model-based process and technology by which a structured multi-layered organization of information obtained by different stakeholders can be gathered, and a multidisciplinary collaboration amongst them could be achieved [10]. Building Information Models (BIModels) are progressively being applied throughout the life cycle of buildings, serving various applications, expanding from the design, construction, and maintenance processes. Furthermore, BIM can be used to enhance the sustainability of buildings over their life cycle [11].

Recent review papers on the application of BIM for LCA highlight the increasing number of publications [9,12–14]. Most existing studies present methods for BIM-based LCA with application in a specific design phase [13]. They either focus on an early conceptual phase [15,16], relying on simplified methods for applying LCA and resulting in not precise outcomes, or on a very late detailed phase [17,18] when accurate information about the building is available, but it is too late for design changes to be performed. Furthermore, most BIM-based LCA studies do not declare a Level of Development (LOD) [9]. Very few studies use different LOD as a basis for the assessment [13,19]. Hollberg et al. [20] show a weekly application of LCA throughout the design process.

However, all these approaches require additional effort for practitioners to carry out the LCA. For BIM-LCA integration, the collection of data about materials and information regarding their quantities is needed. The process of re-entering the data in environmental assessment software is time-consuming and typically not done by the specialists involved in the creation of the BIModels [21]. Moreover, companies lack the incentive to perform LCA since it is usually not demanded in their working processes. Some countries, such as France or the Netherlands, have introduced the need for mandatory green building certification systems in which LCA is often required in order to gain a building permit. Still, the methodology for assessing environmental impacts is not compulsory on a large scale. In that sense, the embodied environmental impacts optimization opportunities are reduced.

Therefore, there is a need to use already existing BIM workflows and structures for the application of LCA. Such an established computational workflow is cost estimation. Cost estimation computations are regularly applied, and their workflow precisely developed in each part of the building process. BIM has been used for cost estimation in different related Levels of Development (LOD) before [22]. Furthermore, researchers have successfully linked Life Cycle Costing (LCC) and LCA [23]. However, the resulting framework is new and very complex, leading to a reduction of the uptake by practitioners.

There is a potential for BIM-LCA integration by adding LCA specific data to the information required for cost estimation, building upon the existing workflow that companies already use today and, as such, giving companies the possibility to apply LCA methods without additional effort.

The main objective of this paper is to develop an integrated BIM-LCA workflow for the entire building process using an existing structure for cost estimation in Switzerland. By using this established and widely adopted structure, the novel approach aims at minimizing the need for re-entering data and the usage of many different software tools. It should provide a methodology for Swiss companies to perform LCA continuously over the whole building process without additional effort. The building phases part of the building process in Switzerland, and their related Levels of Development (LOD) are reviewed so that the needed information required to perform LCA is identified. Existing LCA databases in Switzerland that can provide the needed data are examined. Current techniques used to structure BIModels according to common code structures for cost estimation are analyzed. Based on that, a new process-structured LCA database is formulated, and a new BIM software tool is developed. The presented workflow and the corresponding tool are tested using a case study.

2. State of the Art

2.1. Building Phases in Switzerland (SIA) and Level of Development (LOD)

The Swiss National Organization of Engineers and Architects SIA *(Schweizerischer Ingenieur- und Architektenverein)*, distinguishes six building phases—Strategic Briefing, Preliminary Studies, Project, Invitation to Tender, Construction and Facility Management.

Every BIM software tool creates a different data structure [24]. Röck et al. [8] point out that the quality of a BIModel depends on its Level of Development (LOD). The authors highlight that the LOD depends on two other factors, namely Level of Geometry (LOG) and Level of Information (LOI). For the environmental impact to be better understood, both the geometrical and the data structure of the BIModel should be examined [24]. In general, the LOD concept proposes for the building process to start with generic, yet representative elements, that are being refined continuously throughout the design decision-making process [7]. Curschellas et al. [25] from Bauen Digital Schweiz (BDCH) and buildingSMART Switzerland (bSCH, part of BuildingSMART International) develop definitions for LOD, LOG, and LOI in the context of the country. Maier et al. [26] develop a BIM Workbook (for BDCH and bSCH). In their study, the authors associate the Swiss building phases defined by SIA to LOD [27]. Each different LOD is related to an existing building phase.

2.2. LCA Databases for Buildings in Switzerland

In contrast to conventional LCA, most LCA studies for buildings use predefined data such as Environmental Product Declarations (EPD) or values from building material LCA databases. As such, the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA), as defined in ISO-14040 are merged into one stage [28]. The quantities of different materials can be directly multiplied with the values from an LCA database. The Swiss LCA databases contain different environmental indicators, including grey energy [29], GHG emissions [3], and a single-score indicator called *Umweltbelastungspunkte/Environmental impact points* (UBP). This indicator is calculated explicitly for Switzerland based on the method of ecological scarcity [30]. In this study, the LCA calculation is evaluated with LCA values and LCA benchmarks. The LCA values provide information for environmental indicators of a specific material or component, whereas LCA benchmarks suggest a recommended estimation.

Different Swiss LCA databases for buildings use different reference units for the LCA values. All these databases use LCA data from Ecoinvent ver. 2.2 (ecoinvent, Zurich, Switzerland) [31].

Area-based LCA databases use the surface area of building components (m^2) and the floor area (m^2) to calculate the environmental impact. They allow for the first estimation of LCA parameters at the beginning of the building process. An example of such a database is the SIA2040 (*SIA-Effizienzpfad*

Energie/SIA-Energy-efficiency path) [32]. The SIA2040 provides estimation and prediction of LCA parameters during building phases 1 and 2 (Strategic Briefing and Preliminary Studies) in the areas of design, operation, and mobility. Through a calculation based on SIA2040, a preliminary analysis can be done, and the potential LCA evaluated.

Component-based LCA databases provide information regarding LCA parameters for different building components (m^2). An example from Switzerland is the *Bauteilkatalog/Component catalogue* [33]. The database combines building component data from BFE (*Bundesamt für Energie/Federal Office of Energy*) [34]/Hollinger Consult GmbH [35] and LCA data from KBOB (*Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren/Coordination conference of the building and real estate bodies of the public building owners*) [36]/eco-bau [37]/IPB (*Interessengemeinschaft privater professioneller Bauherren/Interest group of private professional builders*) [38]. In this way, the building components are evaluated according to LCA parameters per m^2 for their more straightforward implementation and decision-making basis provision.

Material-based LCA databases provide information regarding the environmental impact of different building materials. A Swiss material-based LCA database example is the KBOB/eco-bau/IPB database. The information regarding LCA provided by the database is based on volume (m^3) or mass (kg) of building materials.

2.3. Cost-Planning Structure in Switzerland (eBKP-H)

A cost-planning structure for buildings—eBKP-H (*Baukostenplan Hochbau/Cost-plan buildings*), developed by crb (*Schweizerische Zentralstelle für Baurationalisierung/Swiss central office for building rationalization*) [39], is used by most Swiss construction companies for cost estimation. The structure covers the building process up to building phase 5 (Construction) [40]. Different eBKP-H groups are associated with different building phases and LOD throughout the entire building process. As the building process evolves, more detailed information is provided for the eBKP-H groups (Figure 1).
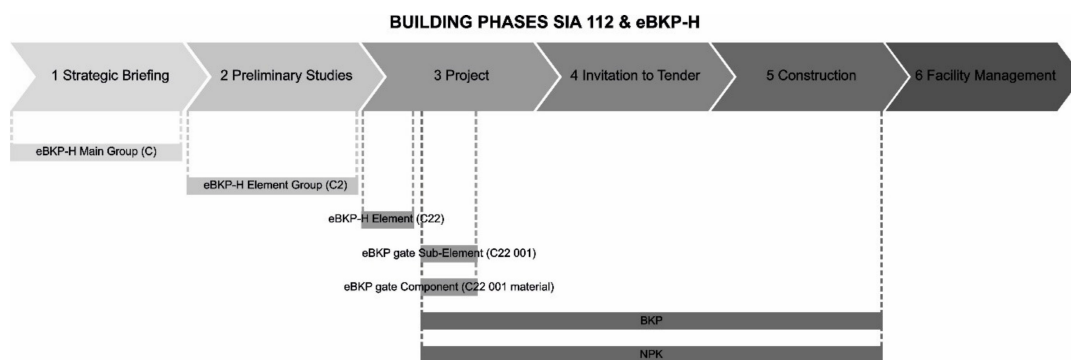

Figure 1. Cost-planning structure for buildings over the building process (eBKP-H—Baukostenplan Hochbau/Cost-plan buildings, BKP—Baukostenplan/Cost-plan, and NPK—Normpositionen-Katalog/Standard positions catalog) developed by crb [40].

3. Methodology

The method for developing an integrated BIM-LCA workflow for the whole building process consists of four main steps. First, the relationship between the building phases in Switzerland (SIA) and the Level of Development (LOD) is identified. Second, the relationship between LCA databases in Switzerland and the Swiss cost-planning structure (eBKP-H) is determined. Third, based on the relation between the building phases, the LOD, the LCA databases, and the cost-planning structure, a new, process-structured LCA database for building components is developed. Fourth, the newly developed LCA database is connected to a BIModel employing a dynamic tool. The tool is applied in a case study building to validate the applicability throughout the building process. The methodology is used for the evaluation of the structural elements part of the BIModel of the case study. The general

concept behind the methodology is to connect the workflow for BIM-LCA integration to the one used for cost estimation by adopting the same BIM elements code-structure.

3.1. Relationship between the Building Phases in Switzerland (SIA) and the Level of Development (LOD)

The building phases and the related LOD are mapped throughout the entire building process while pointing out their relation to the LOG and LOI. As the process evolves, building components and materials part of it are better defined. The building process is divided into two parts. From building phases 1 to 3, a simplified component-based approach is considered, while from building phases 4 to 6, a detailed material-based approach is proposed (Figure 2).
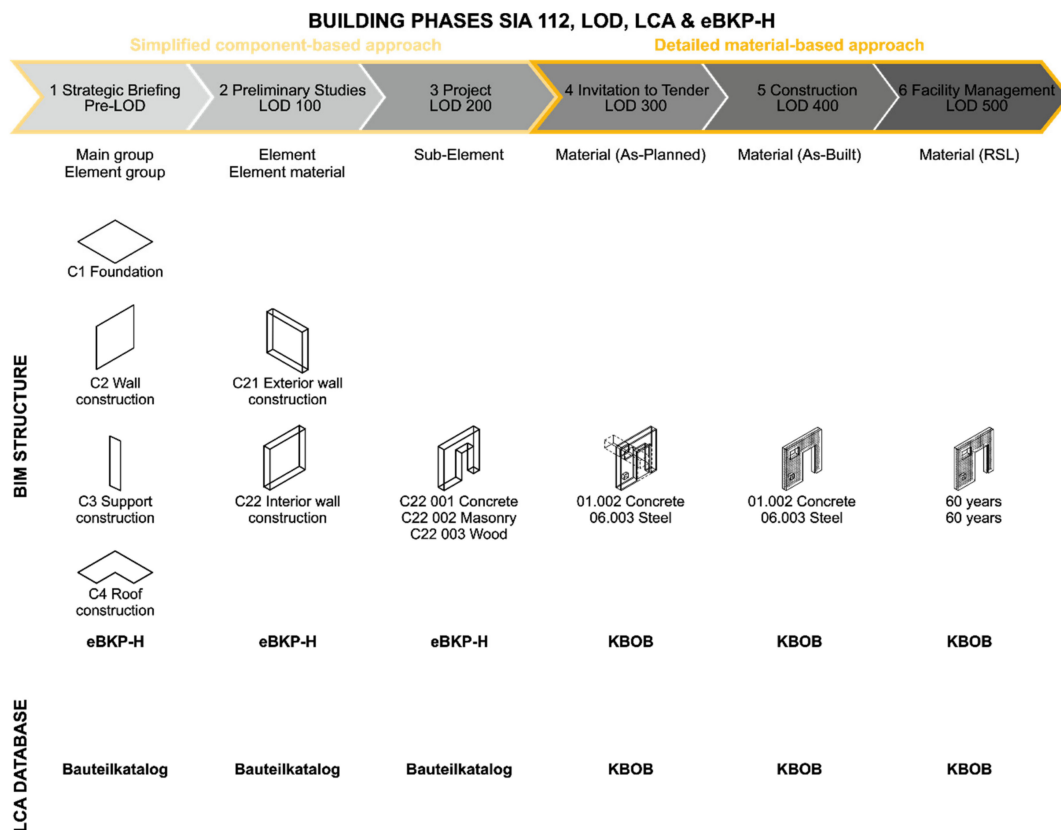

Figure 2. Relationship between the building phases in Switzerland (SIA—Schweizerischer Ingenieur- und Architektenverein/Swiss National Organization of Engineers and Architects), the Level of Development (LOD), the Life Cycle Assessment (LCA) databases in Switzerland and the Swiss cost-planning structure (eBKP-H—Baukostenplan Hochbau/Cost-plan buildings).

3.2. Relationship between the LCA Databases in Switzerland and the Swiss Cost-Planning Structure (eBKP-H)

The LCA databases used for the evaluation of the building process are the *Bauteilkatalog* and the KBOB database. The *Bauteilkatalog* provides information regarding the simplified component-based approach, while the KBOB database serves for the evaluation of the detailed material-based one. The information in both the *Bauteilkatalog* and the KBOB database is derived according to Ecoinvent data version 2.2 [31] and covers life cycle modules A1–A3 (production), B4 (replacement) and C3–C4 (disposal). This information is then used and evaluated per year of building life cycle for building phases 1-5. For building phase 6, information regarding the Reference Service Life (RSL) is used to identify when should the materials part of the building be changed.

For the assessment of the simplified component-based approach, the cost-planning structure provided by eBKP-H is used and mapped with LCA data for different building elements and sub-elements. The cost-planning structure is used as a base for the evaluation of the detailed

material-based approach as well, mapping the eBKP-H building elements structure with the KBOB material one.

3.3. New Process-Structured LCA Database

The identified relationship between the building phases (SIA) and the Level of Development (LOD) is associated with the recognized relationship between the LCA databases and the cost-planning structure (eBKP-H). A new process-structured LCA database is composed following the identification. LCA values and LCA benchmarks are provided by the database. The database is later incorporated in automated workflow and a dynamic tool for LCA, leading to the achievement of BIM-LCA calculation and integration.

For the evaluation of the simplified approach, building components with different LOD are taken into account. Since there is enough information regarding the concept of the building itself in building phase 3, it is assessed with specific values of building Sub-Elements. In building phase 2, most commonly used building Sub-Elements are taken into account and grouped according to the Element or Element Material groups. These groups are evaluated with an average value, based on the Sub-Elements that are composing them. A similar logic is applied for the evaluation of building phase 1—building Element Groups are evaluated with an average value from building phase 2. For the detailed approach, information regarding the building materials is assessed. In building phase 4, data about the materials As-Planned is used, while in building phase 5, information about the As-Built materials is used. In building phase 6, the materials are evaluated based on their Reference Service Life (RSL). In that way, the whole building process is evaluated, providing a method for LCA that is applied continuously over the entire building process (Figure 2).

3.4. Developing a Link between the New Process-Structured LCA Database and BIM—Dynamic Tool for LCA

A dynamic tool for LCA is developed to link the new process-structured LCA database and the BIModel. The tool is created in the parametric program Dynamo and connected to the BIM software tool Revit. A case study analysis is used as a research approach for the development of the link. The aim behind the implementation of the new process-oriented LCA database into a dynamic tool is to provide an automated method for a BIM-based LCA calculation, leading to a BIM-LCA integration.

Through the creation of the tool, a dynamic workflow is developed (Figure 3). The workflow uses the existing code-structure for cost estimation, part of the BIModel, and links it to LCA values from the new process-structured LCA database. Building components' quantities are extracted and multiplied with the LCA values, providing information about embodied environmental impacts for the different components and the building itself. In that sense, the tool builds upon the existing methodology for BIModel creation and the workflow for cost estimation, by adding additional value through the evaluation of embodied LCA impacts.

Three steps are followed for the development of the link: LCA parameters creation, calculation and check, and LCA Report. Through the LCA parameters creation, LCA parameters are calculated, checked, and filtered for their evaluation and visualization. The results are then exported in the form of an LCA Report.

3.4.1. Step 1: LCA Parameter Creation

The first step is related to the creation of LCA parameters in Revit. The reason behind this is to provide a basis for the evaluation of building components, part of the BIModel geometry. Native BIM libraries do not contain information regarding specific LCA parameters and lack a basis for the provision of environmental evaluation. The LCA parameter creation enables the possibility for assessment of building geometries.

Parameters related to grey energy, GHG emissions, and UBP are created and incorporated in the BIModel. Once the parameters are created, they are assigned to different Revit element categories (e.g., walls, floors, roofs). The values are extracted from the new process-structured LCA

database. The database provides information regarding LCA values and LCA benchmarks for both the calculation and evaluation of building components. The automated creation of project parameters in Revit eliminates the need for manual parameter input.
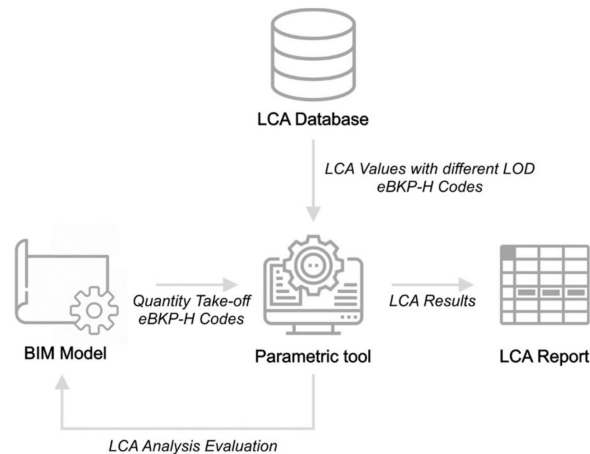

Figure 3. Developing a link between the new process-structured LCA database and the BIModel—dynamic workflow.

3.4.2. Step 2: Calculation and Check

The second step is related to the calculation of LCA values [33] and the check of LCA benchmarks [29,41] at both the element and building levels [42].

The calculation is done through a mapping of eBKP-H codes part of the new process-structured LCA database to eBKP-H codes assigned to building components. The quantities of the building components are derived from the BIModel. LCA values with different LOI can be extracted from the LCA database according to the building phase and the LOD. After extraction, LCA values are multiplied with the respective building element quantities from the BIModel. The results are then filled in the LCA parameters created during the first step and compared to the LCA benchmarks. Subsequently, the calculation and check at the element level, the same is accomplished at the building level. The calculated LCA values for all building components are gathered and associated with the Energy Reference Area (ERA) [42] of the building, providing a decision metric on a building level. The building elements' surfaces (for an indication on element level) and lines (for an indication on building level) are colored with three colors: red (above), orange (at), and green (below) following the LCA benchmarks (Figure 4). As such, the second step provides a decision-making metric through visualization on both element and building levels for the overall optimization of the evaluated building.
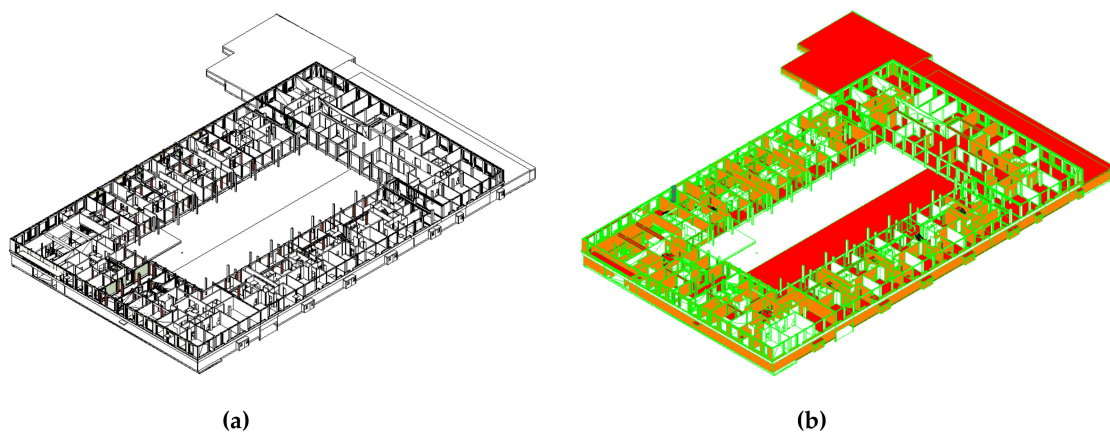

(**a**)　　　　　　　　　　　　　　　　　　　　(**b**)

Figure 4. Dynamic tool for LCA—Step 2: (**a**) Calculation and (**b**) check.

3.4.3. Step 3: Report

With the implementation of the third step, an LCA report is created. The values for all the LCA parameters are collected and summed up according to the different element groups. Finally, the information is extracted and input in an Excel sheet, while creating a table and graphs with the respective values on the respective LOD.

3.5. Case Study Description and Dynamic Tool for LCA Test and Calibration

The case study is provided by the Swiss construction company Implenia. Implenia is a leading construction and construction services firm in Switzerland. It also has strong positions in the German, French, Austrian, Swedish, and Norwegian infrastructure markets, as well as significant building construction and civil engineering operations in Germany and Austria [43].

The case study itself is a mixed-use timber building called Krokodil (Figure 5). The building is located in the Lokstadt district, in Winterthur, Switzerland. The project uses a three-dimensional data model throughout the whole process, from the architectural competition to the execution planning. It has started in 2016 and is expected to be completed in 2020. The gross floor area of the building is 31,559 m^2. The building is composed of eight floors above ground level and two floors below. The timber construction of the building is composed of prefabricated elements and entitles for most of the structures used in the building, leading to a reduction of the embodied environmental impacts.
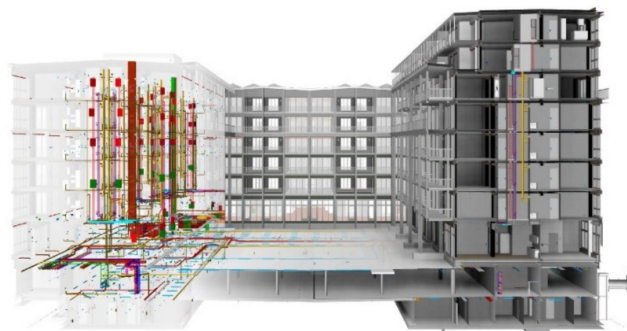

Figure 5. Case study—mixed-use new building Krokodil, Lokstadt, Winterthur, Switzerland [43].

One of the main strategic goals of the project design is the achievement of the sustainability targets set by the 2000-Watt Society. The 2000-Watt Society is a program created by The City of Zurich that defines target values for the 2050 year of 3500 Watts and two tonnes of CO_2-eq per person. The program sets goals related to consumption, settlement, buildings, energy supply, and mobility for reaching these target values. Regarding embodied environmental impacts, the program refers to the Swiss Minergie-ECO standard [44]. Minergie-ECO accounts for embodied energy used in buildings through the identification of grey energy (MJ), GHG (kg CO_2-eq), and UBP (Pt.) [42].

The structure of the BIModel reviewed during the case study analysis is composed according to the eBKP-H structure. eBKP-H provides a methodology that is acknowledged for BIModel creation and elements identification through a code-base system for cost estimation. Each building element part of the BIModel of the case study building is associated with a code for its identification. In that way, information derived from the new process-structured LCA database can be associated with the code system provided by the cost-planning structure.

The case study analysis helps for the derivation of the results. For that purpose, two floors of the building are extracted for their prompt evaluation. In that sense, the results provided by the assessment do not resemble the environmental impact of the whole building. The developed dynamic tool for LCA is tested in the case study and calibrated according to the results.

4. Results

4.1. Process-Structured LCA Database

Through the developed relationship between the building phases in Switzerland (SIA), the Level of Development (LOD), the LCA databases in Switzerland, and the Swiss cost-planning structure (eBKP-H), a new process-structured LCA database is created (Figure 6). The database accounts for the simplified component-based approach (Figure 6). It is structured according to building phases 1-3 (Strategic Briefing, Preliminary Studies, and Project) [27] and their related LOD (Pre-LOD, LOD100, and LOD200) [25]. The building phases mapped with LOD are then related to the existing code-based structure for cost-planning (eBKP-H Main Group, Element Group, and Element) [39]. Data from existing LCA databases regarding building elements are used to provide LCA values [33] and LCA benchmarks [22,29] for the Sub-Element groups. These data are then related to the eBKP-H groups above the Sub-Element groups by taking an average number of the components part of each group.

Figure 6. New process-structured LCA database, Element C22 Interior wall construction.

4.2. Dynamic Tool for LCA

The developed link between the new process-structured LCA database and the BIModel results in a dynamic tool for LCA. The tool is generated in the software program Dynamo and applied to the case study building BIModel (see more in Supplementary Materials). The results provide information regarding grey energy (MJ/a), GHG (kg CO_2-eq/a) and UBP (Pt./a) in different building Elements and Sub-Elements groups (e.g., C, C2, C22), referring to the information provided from the new process-structured LCA database (Figure 6).

On Figure 7, results derived after running the Dynamo scripts on BIModels from building sub-phases 22 (2 Preliminary Studies—22 Selection Procedures), 31, and 32 (3 Project—31 Schematic Design, 32—Design Development) with different LOD regarding grey energy (MJ/a) are shown. The results account for the simplified component-based approach for LCA (Figure 2) by evaluating the different LOI in terms of embodied environmental impacts based on the different building phases. The results follow the evolution of the BIModel, providing more precise information in each further phase. The detailed material-based approach has not been included in the new process-structured LCA database, and therefore, is not part of the results.
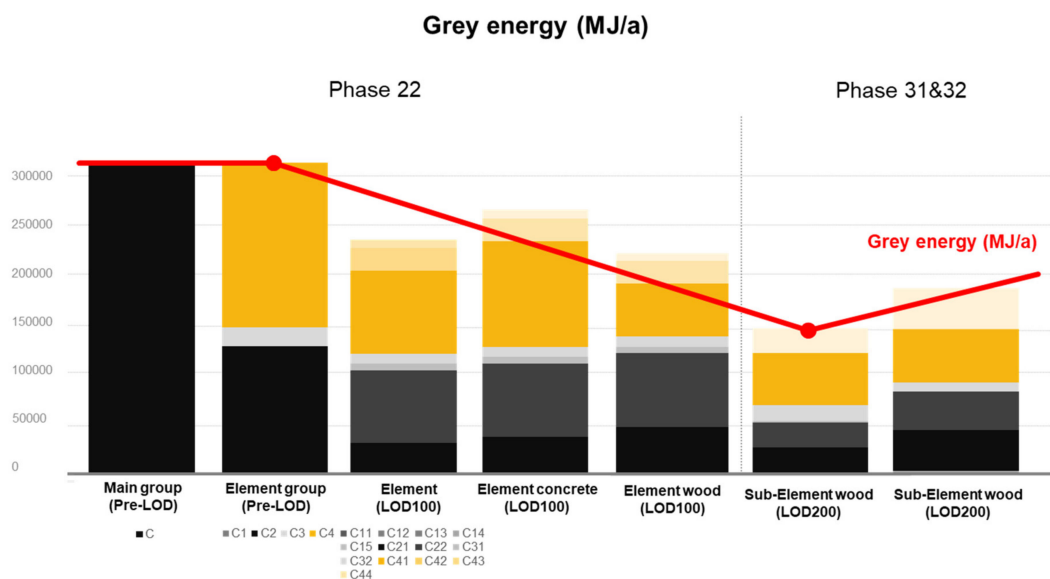
Figure 7. Test and calibration of dynamic tool for LCA.

On the BIModel from building sub-phase 22 calculations regarding Main Group and Element Group (Pre-LOD), and Element and Element Material (LOD100) are performed. Changing the Level of Development from Pre-LOD to LOD100, different Elements are distinguished from the different Element Groups, providing more precise information regarding each Element. In LOD100, the impact of varying Element materials is highlighted. Results regarding Element Material Concrete (LOD100) and Element Material Wood (LOD100) are compared to Element (LOD100).

The results from building sub-phases 31 and 32 are regarding Sub-Element Materials (LOD200). For their derivation, specific wooden building components with low LCA values from the LCA database are chosen. Comparing the results between building phase 31 and 32, the grey energy is increasing.

5. Discussion

5.1. Limitations

5.1.1. Information Modeling

Incompleteness of BIModels

There are limitations related to the incompleteness of BIModels. These limitations can also be associated with the incompleteness of the IFC files used for their creation. Furthermore, the incompleteness of BIModels can be caused by issues related to the application of IFC models to different BIM software tools. Two general trends are identified in relation to these limitations. The first one is related to missing building elements (e.g., HVAC elements) and building sub-elements (e.g., finishing plaster within a wall element). The second one is regarding missing parts of the BIModel geometry as well as information assigned to it (e.g., different parameters or eBKP-H codes). These limitations lead to an incomplete BIModel and incomplete Bill of Quantities (BOQ), respectively, imprecise LCA results.

BIModels' LOD

Some building elements (structural elements) are defined before others (claddings). These issues lead to variability between the LOD of different components. Another critical point in that sense is that even if structural elements are defined, the materials they are identified with still do not represent the same LOD as the BIModel. For example, composite walls composed of concrete and steel are modeled with only concrete as a material. That means that if such elements are evaluated in terms of grey energy

and other LCA parameters based on their material content, such evaluations will not represent the actual LCA values. Therefore, it can be concluded that the usage of some materials in BIM is slightly related to a group of materials rather than to a particular single one.

BIModeling Techniques

The concept behind the dynamic tool for LCA and the related workflow developed in this study are strongly associated with the modeling techniques used in BIModels. The main idea adopted from these techniques is that different building elements in the BIModel are distinguished with codes adopted from the Swiss cost-planning structure for buildings developed by crb (eBKP-H). These element codes are later mapped to an LCA database structured according to the same code system. That means that if the Building Information Modeling (BIModeling) technique does not incorporate such a code system, this mapping would not be possible unless such codes are assigned manually in the BIModel before its LCA evaluation. The limitation can be prevented if element codes are mapped to the model-specific BIM structure in advance. In the case study, the LOD of the codes assigned in the BIModel is LOD100. For that reason, the codes from this LOD are used for the evaluation of LCA in LOD200 as well. That leads to the fact that different Sub-Elements levels could not be identified in different elements levels. For example, all interior walls are considered to be of the same type since they all have the same code assigned. In that sense, a higher level of LOD code differentiation would lead to more detailed results and better decision-making metrics.

5.1.2. LCA Databases

New Process-Structured LCA Database

Using average values for Elements and associating them with Element Groups implies that different Elements are equally distributed in different Element Groups. For example, Element Group C2 Walls is composed of Elements C21 Exterior Walls and C22 Interior Walls. Taking the average value of these two Elements would mean that the Element Group C2 Walls is composed of 50% interior and 50% exterior walls, which is not precise. Still, for an early estimation when there are not sufficient details about the further development of the building project, such simplification can be taken into account for LCA estimation. Hollberg et al. [41] use benchmarks based on the market share of different building materials within Switzerland to provide more realistic values. These could be integrated into the database in the future.

Existing LCA Databases

The main issue with LCA databases is that they do not declare LOD, leading to the possibility of imprecise application time, as well as inaccurate LCA results. Another problem is that LCA databases are inconsistent in terms of the variability of proposed building components and materials used in them. LCA benchmarks are usually not provided by LCA databases and are not identified with LOD. Most databases focus mainly on traditional building components and neglect the usage of more sustainable and bio-based materials. There is also variability in the units used in the databases. Regarding BIM-LCA integration, the biggest challenge associated with LCA databases is their structure and its difference when compared to the BIModeling structure.

5.2. Future Potential

5.2.1. Information Modeling

BIModel Structure

There is a need for a common modeling structure to be recognized and adopted by different specialists when they are developing various building projects. This structure should be associated

with different LOD and their related LOI and LOG. A standard BIM structure used for different project needs has the potential to provide a more straightforward implementation and easier evaluation for the building elements it is applied to. For that reason, researchers and specialists working in different disciplines from the building industry should find common ground for standardization of typical building components, elements, and sub-elements.

The method of using an existing cost-planning BIM structure for LCA evaluation gives construction companies an incentive to implement LCA without additional efforts. Moreover, through the implementation of this automated method, the manual input of data is limited, and hence, the potential of errors caused by the human factor is minimized. Another associated benefit is the capacity to provide decision-making support while implementing LCA values and LCA benchmarks, related to the different building phases and their associated LOD at both the element and building levels.

The method applied in this research strongly relies on the information provided and the structure implemented in the case study developed by the Swiss construction company Implenia. Case studies from other construction companies of the same scale should be reviewed so that different approaches are compared. In addition, case studies from different planning companies, e.g., architectural offices, should be considered as well. The method is also strongly dependent on the existing LCA databases and cost-planning structure in Switzerland. Nevertheless, the method can be adapted to other national contexts using databases and structures from other countries.

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There is a future potential for improvement of the approach, applied in this study, by adopting the following trends:

- Trend 1: Incorporating LCA parameters in the methodology for the BIModel creation (Figure 8);
- Trend 2: Using IFC files for LCA evaluation (Figure 9).

For the first trend, LCA parameters should be part of the methodology during the project creation (Figure 8). If LCA parameters exist in the model from its very beginning, that would allow different specialists involved in the building process to evaluate such parameters in their desired software environment. In that way, the need to import the LCA database in a later phase of the building process would be eliminated. There are several ways in which that can be accomplished. One way is for the LCA database to be incorporated in the form of an openBIM file (IFC). Another is to integrate LCA databases in the form of closedBIM files (Revit, ArchiCAD). Data storage methods (XML, SQL) can also be used for the provision of LCA values.

Trend 1 can be associated with the provision of decision-making metrics while modeling the project.

For the second trend, IFC files could be used for LCA evaluation (Figure 9). That would allow for the BIModel to be created in a desired BIM software tool and then exported in the form of an IFC file. Several criteria are identified related to that approach [23]:

- BIM library requirements, a BIM guideline and a Model View Definition (MVD);
- An IFC file model checker to ensure that the IFC file contains all the relevant information;
- An IFC Viewer Plugin or a newly developed software tool that performs the LCA Evaluation.

For the creation of an IFC-based tool for LCA evaluation, a specific IFC viewer software program is required. This fact comes to imply again that an approach for BIM-LCA integration is associated with the exchange of information between different software programs. The trend can be pointed out as an approach providing consultation on the project regarding the usage of materials in it, rather than improving it by changes on the model itself since its geometry cannot be remodeled.
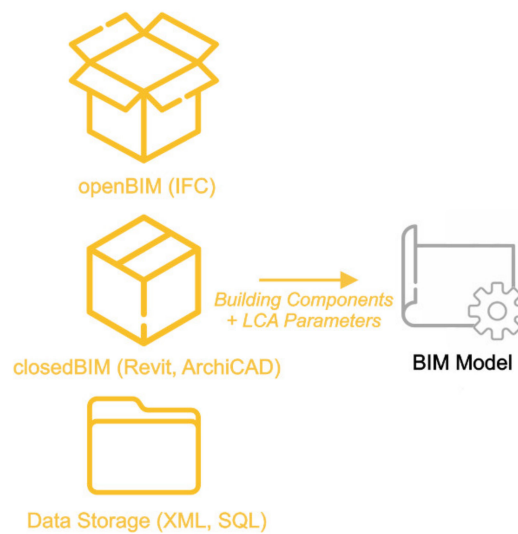
Figure 8. Trend 1: Incorporating LCA parameters in the methodology for the BIModel creation.
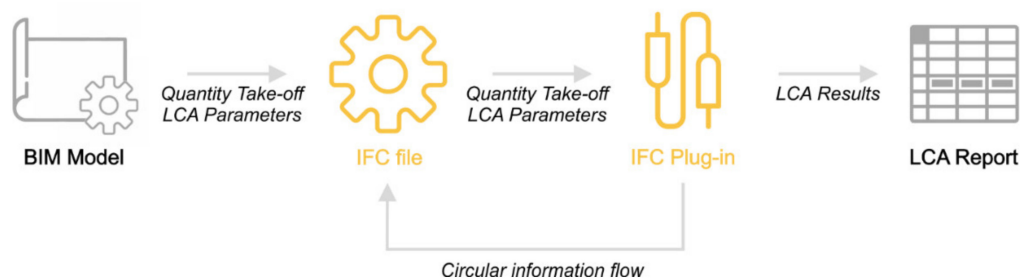

Figure 9. Trend 2: Using IFC files for LCA evaluation.

5.2.2. LCA Databases

Future potential can be identified with further development of LCA databases. Existing LCA databases can be restructured so that different building phases and LOD levels are distinguished. LCA benchmarks should be provided. The databases should adopt a standard generalized code structure that is related to different LOD levels for their more straightforward implementation in BIM. LCA values should be incorporated into existing building components and libraries, BIM families, pre-fabricated elements, technical equipment. At the same time, LCA parameters should be distinguished using a standardized LCA dictionary, which provides keywords associated with LCA so that a common understanding is achieved.

The new process-structured LCA database relies on information from databases, which consist of only traditional components and materials. In that sense, the proposed method is useful for mass construction, but not for innovative construction solutions. The development of databases for bio-based materials, as well as recycled and innovative materials, should be considered for their easier implementation in buildings and for large companies to have a higher motivation to use them.

5.2.3. Dynamic tool for LCA and New Process-Structured LCA Database

Since the dynamic tool for LCA and the new process-structured LCA database are developed until building phase 3, project (SIA), there is a future potential for their development in building phases 4 to 6, adopting a detailed material-based approach for LCA. There is also a potential for the development of a tool with a specific approach for building phase 1, strategic briefing since, in that phase, there is usually no BIModel. This tool can be developed using the software program Grasshopper in combination with modeling software tools like Rhino or ArchiCAD, which are typically associated with providing decision-making metrics during conceptual design phases.

The proposed dynamic tool and workflow for LCA evaluation account only for the embodied energy of structural elements. An embodied energy impact of MEP elements is not considered, due to the incompleteness of the BIModel part of the case study. An operational energy impact is also not considered. However, the same logic can be applied for the future development of a tool and workflow for the evaluation of operational energy. Nevertheless, it is essential to highlight that in newly developed energy-efficient buildings, the impact of embodied energy often exceeds the one from operational energy [45]. In that sense, the dynamic tool and the related workflow developed provide an instrument to account for the contribution of a type of energy in buildings, which has a higher overall impact.

5.2.4. Decision-Making

The results derived after running the dynamic tool for LCA provide only concrete numbers, based on the quantities of the building elements and the building's gross floor area. Still, there might exist other indicators that can be taken into account. For example, if a building element's LCA values are above the associated LCA benchmarks, this element can still be better positioned when related to the whole building than two elements with LCA values at the LCA benchmarks. This issue is partly addressed by the provision of decision-making metrics at the building level, taking into account all building elements and associating them with the whole building. However, there exist other possibilities to provide more precise decision-making metrics, for example, by implementing artificial intelligence opportunities and machine learning. In that sense, these metrics can be pointed out as a way to address decision-making during the building process in the future. Machine learning metrics can also be used for future improvement of the method, for example, for smart mapping of components, elements, sub-elements, and materials. There is future potential in developing similar tools by adopting similar workflows for different purposes, for example, to evaluate operational energy or Life Cycle Costing (LCC). The scripts can be optimized, and their computation done on a cloud source so that the time for their evaluation is reduced.

6. Conclusions

The current study proposes a methodology for companies in Switzerland to perform LCA continuously in each building phase over the entire building process. The method provides decision-making support at both the element and building levels at every building phase and their associated Levels of Development (LOD). For its implementation, to associate the method with an existing BIM workflow, the cost-planning code structure (eBKP-H) applied in BIModels for cost estimation is used. In that way, the methodology proposed in this study provides LCA results using a well-established BIM structure while giving an incentive for construction companies to apply LCA methods in a simplified way.

For the development of the methodology, a new process-structured LCA database is created. The database is structured according to the building phases that are part of the building process in Switzerland (SIA), their associated LOD, Swiss LCA databases, and the cost-planning structure for cost estimation in Switzerland (eBKP-H). By these means, the database provides information about embodied environmental impacts for each building phase and its associated LOD, accounting for the environmental evaluation of the entire building process. Information about both LCA values and LCA benchmarks is provided, giving an incentive for decision-making metrics on both element and building levels, while implementing visualization criteria. Through the implementation of the database, the existing cost-planning BIM code structure (eBKP-H) is used, leading to the prevention of the re-entering of LCA data into the BIModel and building upon the existing workflow for cost estimation. Therefore, an incentive for Swiss companies to apply LCA is given. Another benefit is the prevention of mistakes associated with the human factor, as well as the time-saving opportunities.

The database is linked to the BIModel using a newly created dynamic tool for LCA. The tool connects the BIModel and the LCA database, calculates LCA values, and returns the results in the model. After the results become part of it, they are compared to the LCA benchmarks part of the LCA

database. In that way, decision-making support through color differentiation is achieved, based on the benchmarks for different building elements on the element and building levels. The application of the dynamic tool for LCA provides optimization for the evaluation of materials used in buildings in a simplified way.

BIM integration in different parts of the building process is a powerful approach through which various areas of it can be optimized. Methodologies, similar to the one developed in this study, can be generated to improve specific areas of specialists' daily work. These methodologies can be applied in different case studies providing a proof of concept with different purposes. Information regarding different use cases can be formed according to LOD and an algorithm for their implementation in BIModels provided. This information should be simplified and standardized for its easier assessment in workflows providing different outcomes. Accordingly, simplification and standardization of the building process through its digitalization have the potential to improve its overall sustainability.

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